RESEARCH MEMORANDUM

FLIGHT MEASUREMENTS OF PRESSURES ON BASE AND REAR PART OF FUSELAGE OF THE BELL X-1 RESEARCH AIRPLANE AT TRANSONIC SPEEDS, INCLUDING POWER EFFECTS

By Ronald J. Knapp and Wallace E. Johnson

Langley Aeronautical Laboratory
Langley Field, Va.

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

Measurements have been made on the Bell X-1 airplane to determine pressures on the fuselage base and on the rear portion of the fuselage during level flight with an airplane normal-force coefficient of approximately 0.4 through the transonic Mach number range to a Mach number of 1.19 at an altitude of 45,000 feet. Measurements were not only made throughout this Mach number range in the power-off condition but also with the rocket engine operating in order that some effects of the jet on the pressure for this configuration might be obtained.

The results show that in the power-off condition the fuselage base pressures change from positive at high subsonic flight speeds to negative at low supersonic speeds. Pressures were essentially constant across the base, the level of which agreed well with the values measured on the fuselage side just forward of the base. At the supersonic speeds of these tests the flow along the fuselage expanded supersonically to within 2 feet of the base, at which point a surface compression shock occurred.

The effects of the jet were to increase the pressures on the fuselage base and on a portion of the fuselage forward of the base. The pressures on the base remained nearly constant throughout the Mach number range of the tests. At the subsonic flight speeds the region of jet influence extended about 5 feet forward of the base. At the supersonic speeds the region diminished to about $1\frac{1}{2}$ feet forward of the base at a Mach number of 1.19, the limit of the tests.

Throughout the Mach number range of the tests the operation of the rockets resulted in a favorable decrease of fuselage and fuselage base pressure drag.

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INTRODUCTION

The fuselage base pressures and pressures over the converging rear section of the fuselage are of considerable importance because of the role they play in making up the fuselage drag. Of further interest are the changes in these pressures due to the addition of a jet issuing from the fuselage base. These changes may have either a favorable or detrimental effect on the fuselage drag, depending upon the jet conditions.

The NACA High-Speed Flight Research Station at Edwards Air Force Base, Calif., is at present conducting flight tests in the transonic speed range with the Bell X-1 rocket research airplane. During recent flights, base- and fuselage-pressure measurements were made to determine the fuselage base pressures in power-off and power-on conditions, wing lift carry-over to fuselage, and total fuselage loads.

The purpose of this paper is to present an analysis of the pressure-distribution data obtained over the fuselage base and over the rear portion of the fuselage in level flight at a high altitude and at transonic Mach numbers. Also presented are the effects of the operation of the rocket engine upon these pressures.

SYMBOLS

M	free-stream Mach number
n	normal load factor
W	airplane weight, lb
q	free-stream dynamic pressure, lb/sq ft
A	maximum fuselage cross-sectional area (16.5 sq ft), $\pi {r_{max}}^2$
S	wing area, including area projected through fuselage, 130 sq ft
S_{B_2}	total fuselage base area, 1.26 sq ft
S_{B_1}	fuselage base area excluding area of operating rockets
C_{N_A}	airplane normal-force coefficient, nW/qS
r_{max}	maximum fuselage radius, 2.29 ft
L	fuselage length, 31 ft

p local static pressure, lb/sq ft

p_o free-stream static pressure, lb/sq ft

P pressure coefficient, $\frac{p - p_o}{q}$

P_{cr} pressure coefficient for local sonic velocity, assuming no total-pressure loss along streamline from free stream

ΔC_{D_B} decrease in pressure-drag coefficient of fuselage base with addition of power, based on maximum fuselage cross-sectional area A, $\frac{1}{A}\left(\iint_{S_{B_2}} P_{B_2}\, dS_{B_2} - \iint_{S_{B_1}} P_{B_1}\, dS_{B_1}\right)$

Subscripts:

B fuselage base

1 power on

2 power off

max maximum

DESCRIPTION OF AIRPLANE AND ROCKET ENGINE

The Bell X-1 rocket-propelled research airplane used in these tests is shown in figure 1 and a three-view drawing showing the general over-all dimensions is given in figure 2.

The airplane fuselage is a sharp-nosed body of revolution having a fineness ratio of 6.8 with the maximum diameter located at about 39 percent of the fuselage length. The center line of the various fuselage stations sweeps upward gradually from the 79-percent station to the fuselage base where it is 5.5 inches above the center line of the airplane (fig. 3(a)). The circular cross section of the fuselage is modified just rearward of the 79-percent station, tapering gradually to the cloverleaf-shaped section of the fuselage base (fig. 3(b)). Photographs of the rear part of the fuselage and of the fuselage base are shown in figure 4.

A Reaction Motors, Inc. rocket engine, model XLR11-RM-3, using liquid oxygen for the oxidizer and alcohol for fuel, is used to propel the airplane. Each of the four rocket cylinders has a rating of

1500 pounds of thrust and is designed for expansion to sea-level pressure at the jet exit; therefore, a considerably underexpanded jet exists at the altitude of these tests. From measurements of specific impulse a jet-exit velocity of about 6100 feet per second has been determined. The jet-exit Mach number and temperature are estimated to be approximately 2.5 and 1800° F, respectively. A drawing showing the rocket nozzle dimensions and contour is presented as figure 5.

INSTRUMENTATION

Standard NACA recording instruments were used to obtain airspeed, pressure altitude, normal acceleration, and angle of attack. Fuselage surface pressures were measured by two NACA multiple-recording manometers. All records were synchronized by a common timer.

Free-stream static and dynamic pressures were recorded with an NACA high-speed pitot-static tube located ahead of the fuselage nose. The total-pressure tube was of the cylindrical-cavity type described as tube A-6 in reference 1. This type of tube was used because of its insensitiveness to flow inclination. The static vents were located at a distance of 0.6 maximum fuselage diameters ahead of the fuselage nose.

Fuselage surface pressures were measured from flush-type orifices installed in the fuselage skin and fuselage base. The locations of the fuselage orifices near the base are shown in figure 3(a) and the locations of the fuselage base orifices are shown in figure 3(b). Photographs of the orifice installations are shown in figure 4. The orifices were connected to the instrument compartment by $\frac{1}{8}$-inch inside-diameter aluminum tubing. The aluminum tubing was connected to the manometer cells by $\frac{3}{16}$-inch inside-diameter rubber tubing. The aluminum tubing was about 17 feet in length.

MEASUREMENT AND REDUCTION OF DATA

Surface pressures were measured over the left side and base of the fuselage relative to the pressure in the instrument compartment. Instrument compartment pressure was measured relative to the static pressure at the pitot-static tube. The measured static pressure was corrected to free-stream static pressure by use of the radar-tracking method of reference 2.

The effects of lag in the measurement of fuselage and base pressures have been neglected because investigation has shown these effects to be unimportant for the rates at which the pressures were changing in these tests.

The fuselage-base-pressure drag was obtained by the summation over the base of the products of the representative areas, shown in figure 6, and the respective measured pressures. In the determination of base-pressure drag in the power-on condition the rocket nozzle areas of the operating rockets were not used because the force on these areas should be considered as thrust and not as negative drag. In the determination of base-pressure drag in the power-off condition the entire fuselage base can be considered as contributing to the drag; thus, the areas including the rocket nozzles were used.

ACCURACY

Estimations based on the recording pressure instruments and methods of calibration indicate that the accuracies of the reported quantities are as follows:

Mach number, M . . . . ± 0.01
Pressure coefficient, P . . . . ± 0.03

The accuracy of the integrated drag coefficients, based on the accuracies of the pressure recorders, integrative methods, and the coverage of the test data is estimated to be:

ΔC_{D_B} . . . . ± 0.002

TESTS

The data presented herein were obtained from a speed run through the Mach number range from 0.77 to 1.19 with power on, and from a level run with power off, decelerating through the Mach number range from 1.19 to 0.86. The power-on run was obtained with two rocket cylinders on from a Mach number of 0.77 to 0.90 at which point a third rocket cylinder was fired. At $M = 1.00$ the fourth rocket was fired to obtain maximum thrust. All four rockets remained on to a Mach number of 1.19 and then all were turned off. Both the power-on and power-off portions of these data were obtained for an airplane normal-force coefficient of about 0.4 at an altitude of about 45,000 feet. The Reynolds numbers, based on the fuselage length, varied from 33.7×10^6 to 67.1×10^6.

RESULTS AND DISCUSSION

The pressure coefficients obtained from the fuselage base orifices, the fuselage side upper row of orifices, and the fuselage side lower row of orifices during both the power-off and power-on flight throughout the Mach number range are presented in figures 7 to 9, respectively. Complete data are not available for lower-row orifice stations 360, 366, and 369 because of intermittent instrument failure. The fairing of the incomplete data (fig. 9) was accomplished with the aid of similar data obtained during later flights. At various selected Mach numbers plots of the pressure distribution, power off and power on, have been made for the fuselage base and the rearward part of the fuselage side. These pressure-distribution plots are shown in figure 10.

Power-off Pressures

The pressures in the power-off condition, as may be seen in figure 10, remained essentially constant over the fuselage base throughout the Mach number range of the tests. The level of base pressure, however, varied with Mach number throughout this range. Figure 7 shows that these values of pressure coefficient were positive and gradually increased from about 0.10 to a peak of 0.15 as the Mach number increased from 0.86 to 0.95. With a further increase in Mach number the base pressures showed a rapid decrease, became negative at about $M = 1.02$, and reached a value of -0.10 at $M = 1.08$. The value of base-pressure-coefficient level was maintained at this value of -0.10 from $M = 1.08$ to $M = 1.13$, above which it further decreased to a value of about -0.30 as the Mach number was increased to 1.19, the limit of the tests.

For the orifices on the fuselage side nearest the base, the pressures show that there was a definite correlation between the flow conditions at these orifices and the pressure level of the base. This correlation may be seen by comparing the plots of pressure variation with Mach number for orifice station 369 in figures 8 and 9 with those for the base orifices in figure 7. The marked similarity shows that the base-pressure level was adjusted to approximately the value of the pressure on the fuselage just forward of the base.

The pressure-distribution plots for the rearward portion of fuselage (fig. 10) show that with power off the lower-orifice-row pressure coefficients remained nearly constant at a value of about 0.05 for $M = 0.86$. The upper-row values at this Mach number, however, did not remain so constant and showed a peak negative value of -0.21 at station 336. This upper-row variation is not due to formation of a surface shock wave in this region because the values of pressure indicate that the flow throughout the region was definitely subsonic. Upon inspection of the film record traces, no evidence of pressure fluctuation due to separation was found.

As the flight Mach number was increased to 0.97 the peak local Mach numbers become slightly supersonic, but the distribution remains essentially the same as at the lower flight Mach numbers. The flow about the vertical and horizontal tails was probably the main factor affecting the variation of upper-row pressures along the fuselage in this region.

At a Mach number of 1.0 (fig. 10) the pressure coefficients are such as to assure local supersonic flow over the rear portion of the fuselage. A surface shock on both orifice rows is indicated on the distributions due to the adverse pressure gradients near station 360.

As the flight speed was increased to a Mach number of 1.19, the limit of the tests, the power-off flow remained similar to that at a Mach number of 1.00, although the flow did expand to higher supersonic local Mach numbers together with a slight rearward movement of the shock.

Jet Effects

It may be seen from figures 7 and 10 that the operation of the rockets caused marked changes on the airplane fuselage base pressure. In all cases the power-on values of base pressure were greater than the power-off values. In spite of the fact that some of the power-on tests were made with only 2 or 3 rockets operating, only a small nonsystematic variation from a constant pressure across the base could be found throughout all of the power-on tests. The data of figure 7 show that, for the power-on condition, the base pressure coefficients had a value of approximately 0.2 through the Mach number range from 0.77 to 0.90 and also through the range from 1.00 to 1.19, the limit of the tests. There was a slight increase of pressure coefficient to approximately 0.28 through the Mach number range from 0.90 to 1.00. The slight increase in pressure coefficients exhibited at several of the orifices at a Mach number of 0.90 nearly coincided with the firing of a third rocket. However, at a Mach number of 1.00, when the fourth rocket was fired, the opposite effect was evidenced; this result indicated that this slight change in pressure level was a Mach number effect and not due to the rockets.

The design of the rocket nozzles results, at the altitude of these tests, in the jet flow leaving the nozzles at an exit static pressure of approximately seven times the free-stream static pressure. These underexpanded jets expand suddenly upon leaving the confines of the nozzles, with an interaction between neighboring jets such as to force a greater expansion at the outer periphery. This resultant supersonic flow, upon being directed obliquely into the external stream, forms a jet-boundary compression shock at the point of intersection. It is believed that a pressure feedback from the high-pressure region following this shock through the subsonic mixing region between the two streams to the region of the base is instrumental in causing the higher pressures over the base in the power-on condition. The high-pressure region formed by the restricted expansion the jets force upon one another is considered as an additional factor in causing the high pressure on the base (fig. 7).

Reference 3 reports an increasing base pressure coefficient with increasing ratio of jet total pressure to free-stream static pressure for the model tests at a Mach number of 1.91. This effect was evident for ratios of jet total pressure to free-stream static pressure from 3 to 15, the limit of the tests, and was attributed to a pressure feedback similar to that mentioned above. Extremely high ratios of jet total pressure to free-stream static pressure, slightly in excess of 100, existed for the Bell X-1 airplane tests of this paper.

It is apparent from the pressure distributions over the rear portion of fuselage (fig. 10) that this high-pressure feedback was continued forward through the subsonic boundary layer. This condition is true throughout the Mach number range of the tests, the effect being to increase the pressure over the entire portion of fuselage that the jet influence is felt. This region of influence was maintained within the rearward 5 feet of fuselage from a Mach number of 0.86, the lower limit of the tests, to a Mach number of approximately 0.99. At this Mach number the region was suddenly reduced to the rearward 3 feet of fuselage. The region of jet influence slowly decreased to about the rearward $1\frac{1}{2}$ feet of fuselage as the flight Mach number was further increased to 1.19, the limit of the tests. The difference in pressure distribution between the power-off and power-on conditions within the region of jet influence (fig. 10) was larger at the supersonic flight speeds. At these speeds the surface compression shock which occurs in the power-off condition was either moved forward or completely eliminated by the addition of power.

The increased pressure over the fuselage base caused by the jet produced a favorable decrease of fuselage base pressure drag from that with power off. The variation with Mach number of the change in base-drag coefficient is shown in figure 11 to be similar to the difference in base pressure level between power-on and power-off conditions, remained nearly constant at the subsonic speeds and increased with increase of supersonic Mach number. Because of insufficient coverage of orifices over the region of jet influence on the side of the fuselage it was not possible to obtain the change in fuselage pressure-drag coefficient due to power effects. It was apparent from the pressure distributions (fig. 10) that a further favorable decrease of fuselage pressure drag from that with power off would be obtained from this region.

SUMMARY OF RESULTS

Pressure-distribution measurements have been made over the fuselage base and rear portion of fuselage of the Bell X-1 rocket-powered airplane in level flight (normal-force coefficient of approximately 0.4) through the transonic Mach number range to a Mach number of 1.19 at an altitude of 45,000 feet. Measurements were made throughout this Mach number range in the power-off condition and also with the rocket engine operating in order that some effects of the jet on these pressures for the Bell X-1 fuselage configuration and engine installation might be determined. The following results were obtained:

In the power-off condition, the pressures over the fuselage base showed a considerable variation with Mach number, were positive at high subsonic speeds, changed to a negative value near a Mach number of 1.0, and remained negative for the supersonic part of the tests. Pressures were nearly constant across the base at all Mach numbers of the tests. The base pressures and the pressures measured at the fuselage side orifices nearest the base were nearly equal at all Mach numbers.

The pressure distributions along the rear portion of fuselage indicated that, at supersonic speeds in the power-off conditions, the flow expanded supersonically to some point within 2 feet of the fuselage base, at which point a surface compression shock occurred. At Mach numbers below about 0.97 there was no evidence of a shock.

The operation of the rockets affected the pressures over the fuselage base and, in contrast to the power-off condition, there was but little change in the base pressure with increasing Mach numbers. The power-on tests were made with two to four rockets operating, but no systematic effect due to number of rockets on the pressure variation across the base could be determined. In all cases the power-on base-pressure coefficients had a value of about 0.1 to 0.2, which was greater than any of the power-off values measured.

This increase in base pressure caused by the operation of the rockets was carried forward along fuselage side. The region affected by rocket operation was confined to within the rearward 5 feet of the base at Mach numbers from 0.86 to about 0.99 above which the region was reduced and decreased to about $1\frac{1}{2}$ feet from the base at a Mach number of of 1.19.

Throughout the Mach number range of the tests the operation of the rockets resulted in a favorable decrease in the fuselage and fuselage-base pressure drag.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va.

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3. Cortright, Edgar M., Jr., and Schroeder, Albert H.: Investigation at Mach Number 1.91 of Side and Base Pressure Distributions Over Conical Boattails Without and With Jet Flow Issuing From Base. NACA RM E51F26, 1951.

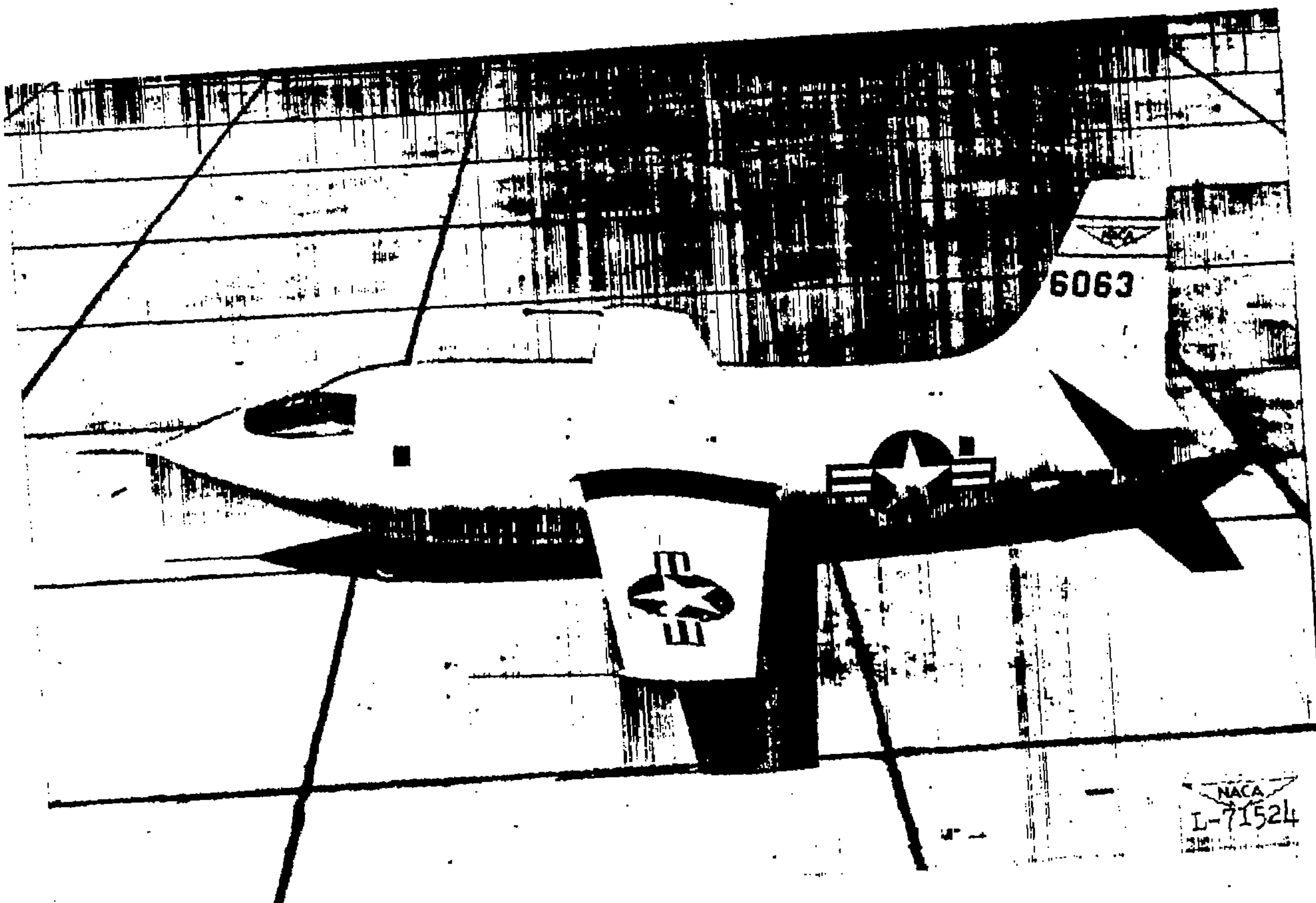


Figure 1.- Overhead side view of Bell X-1 airplane.

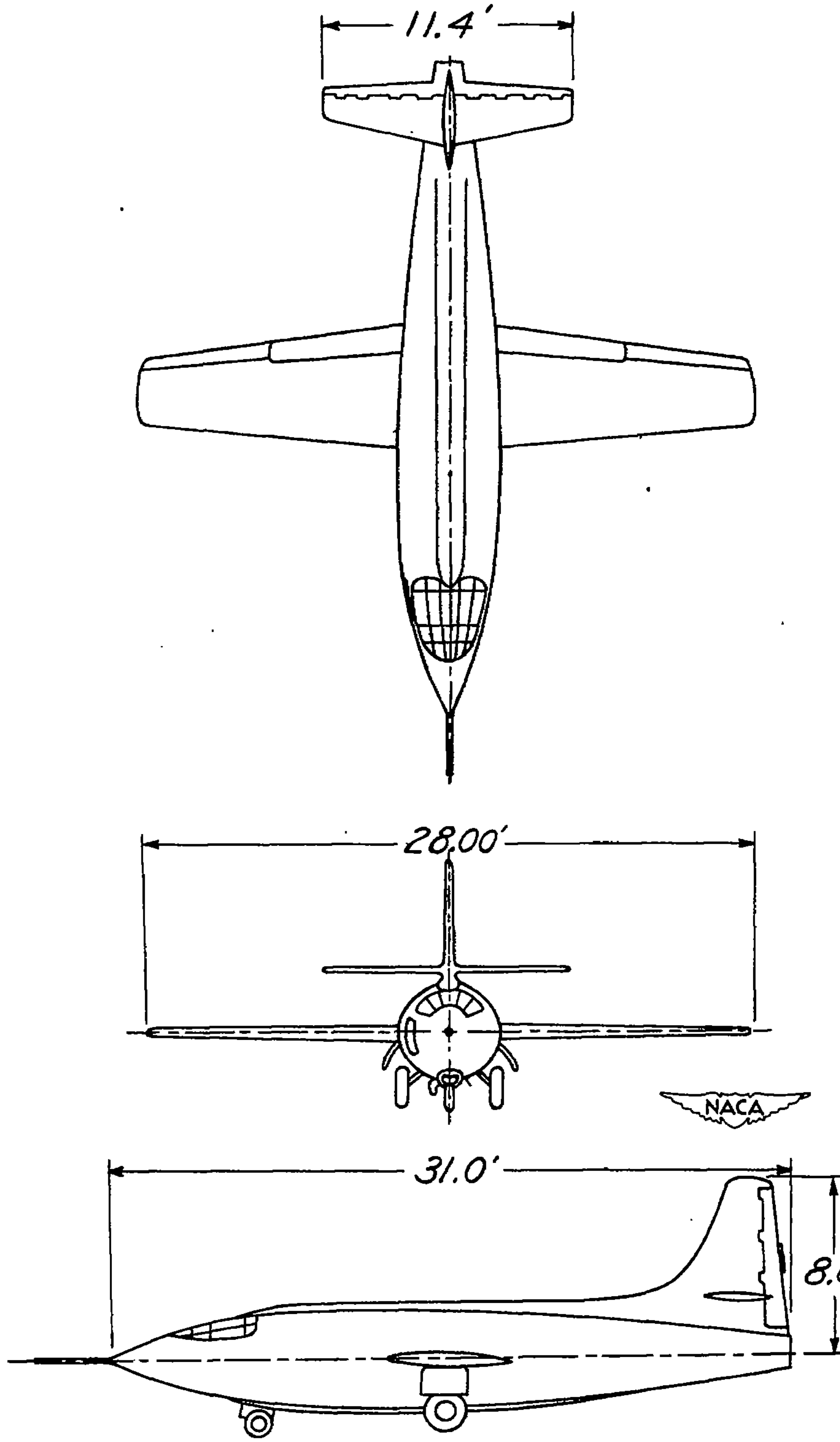
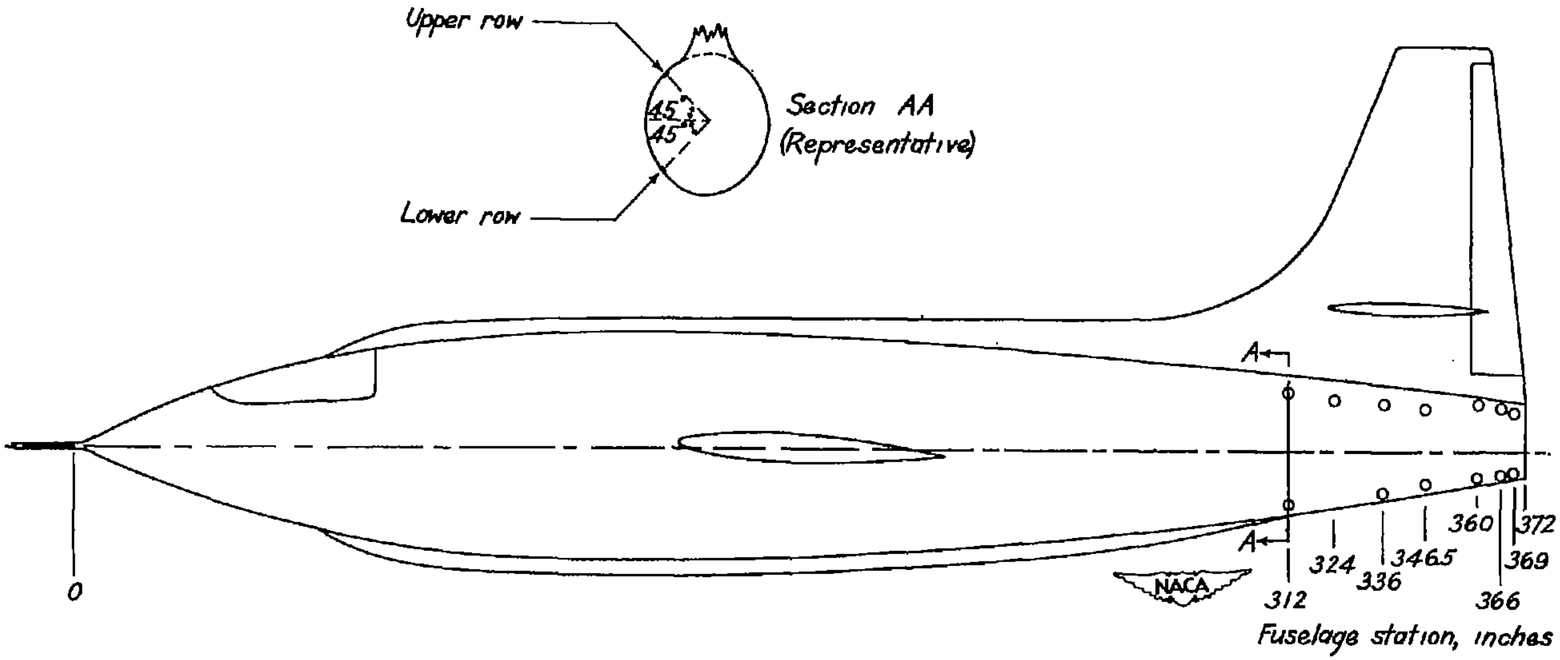
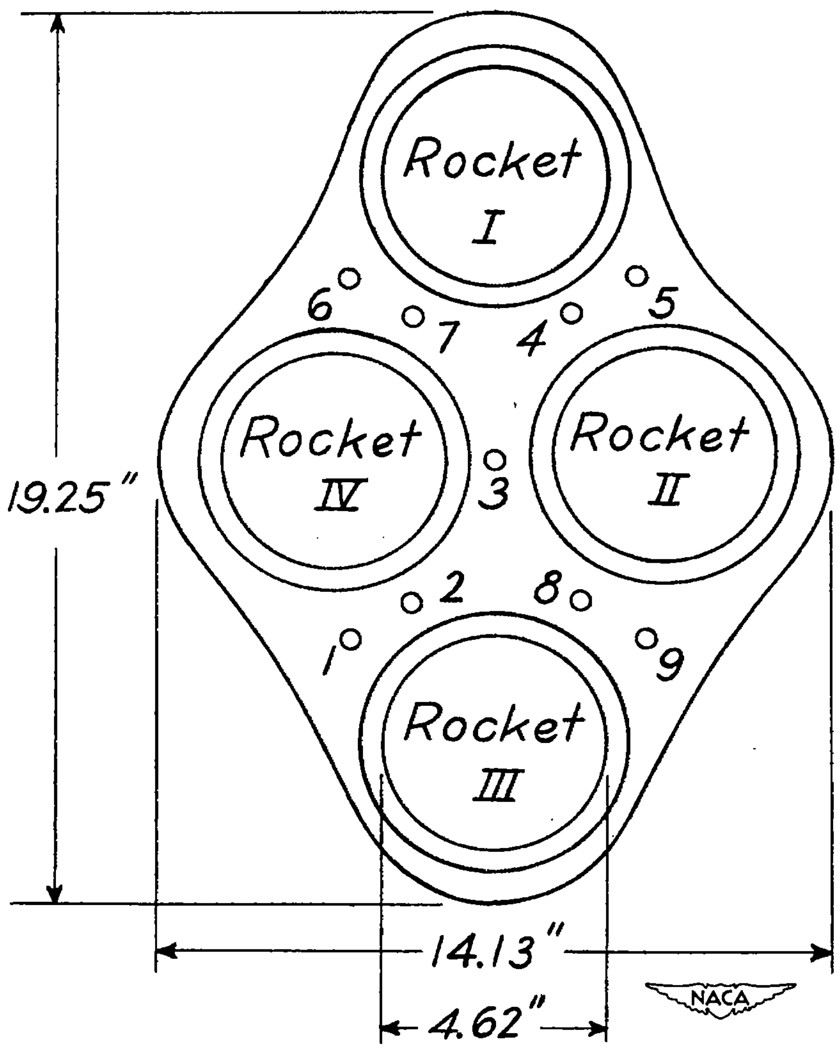


Figure 2.- Three-view drawing of Bell X-1 airplane.



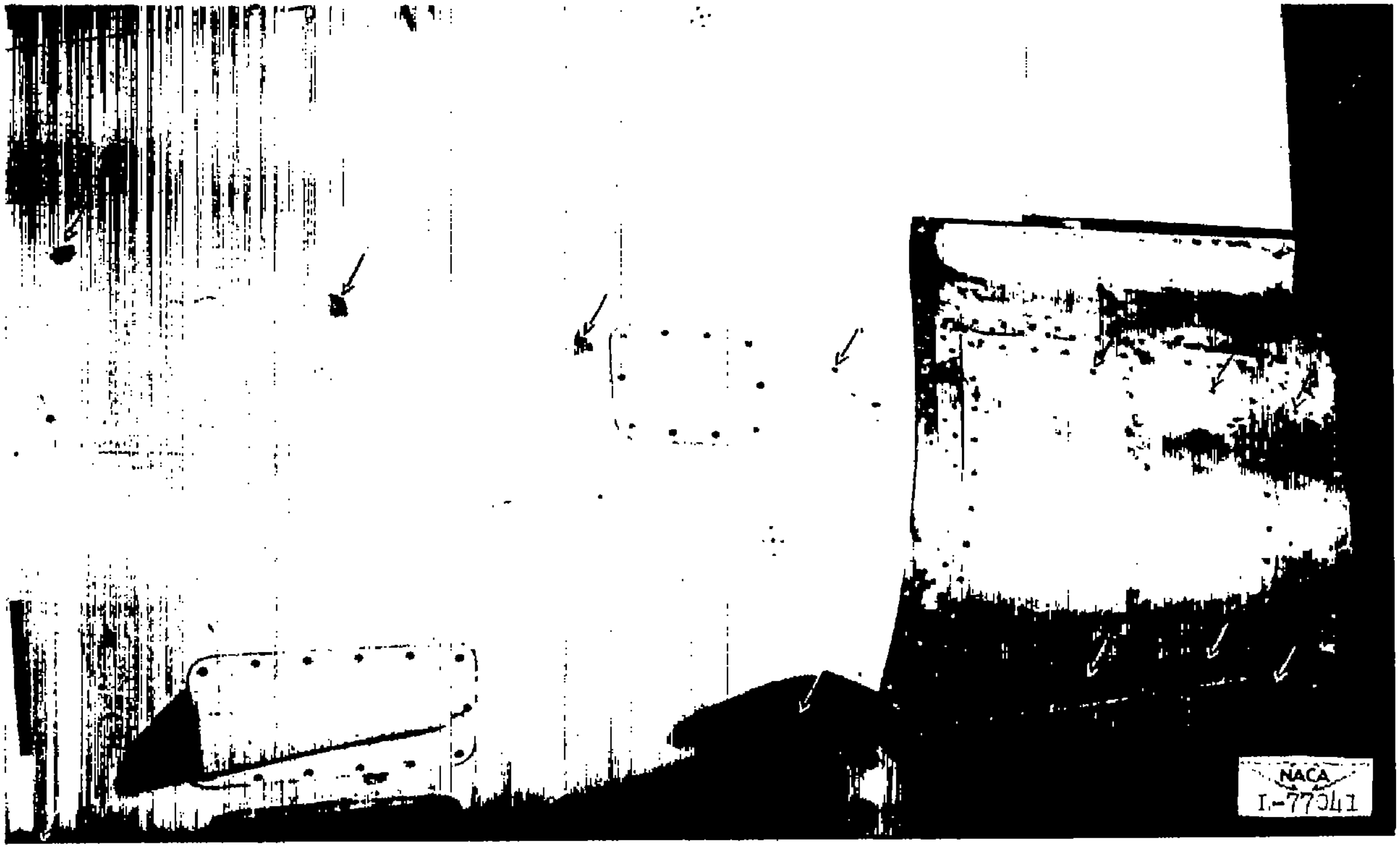
(a) Fuselage side near base.

Figure 3.- Location of pressure-measuring orifices on fuselage of Bell X-1 airplane.



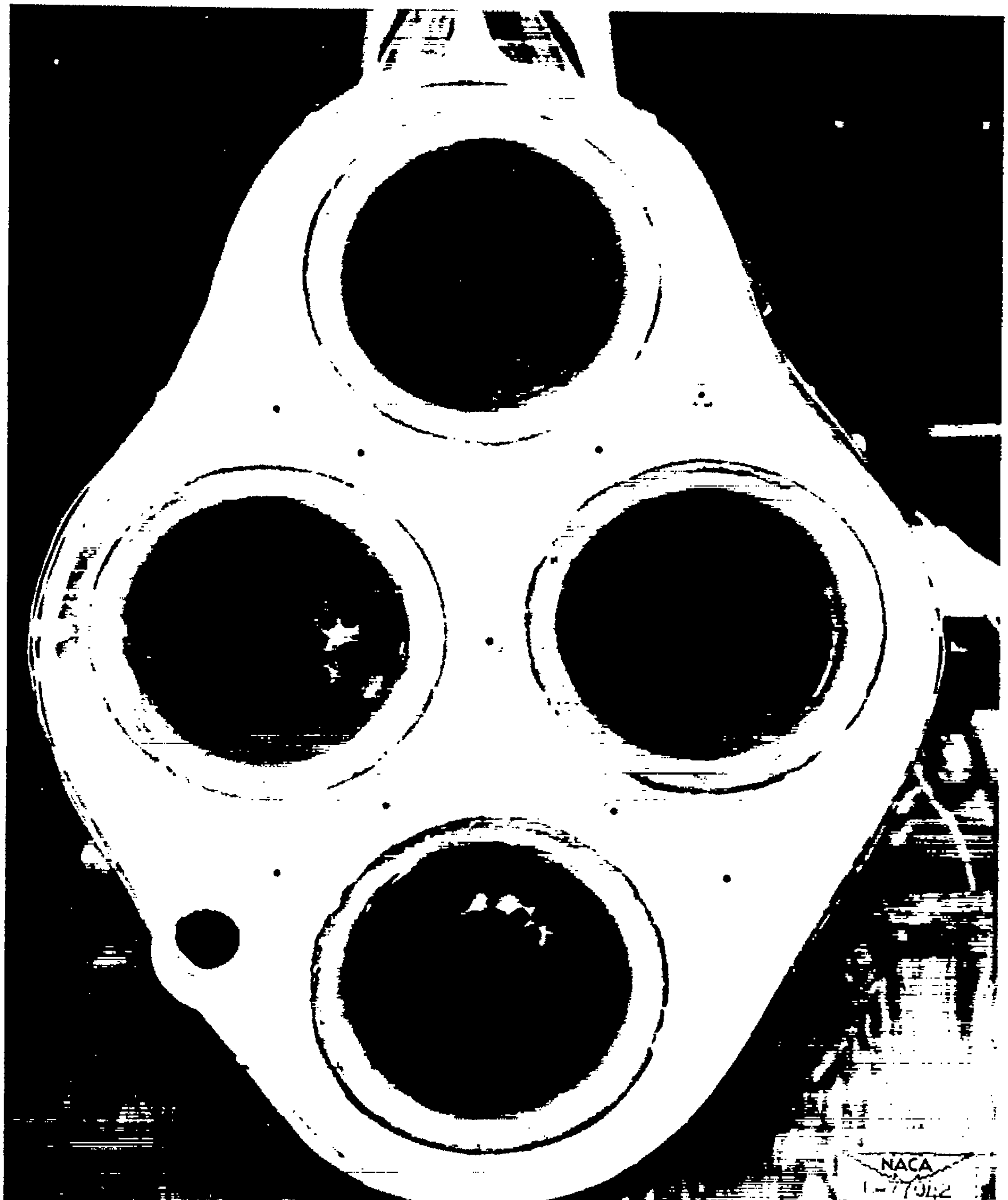
(b) Fuselage base.

Figure 3.- Concluded.



(a) Fuselage side near base.

Figure 4.- Photograph of locations of pressure-measuring orifices on fuselage of Bell X-1 airplane.



(b) Fuselage base.

Figure 4.- Concluded.

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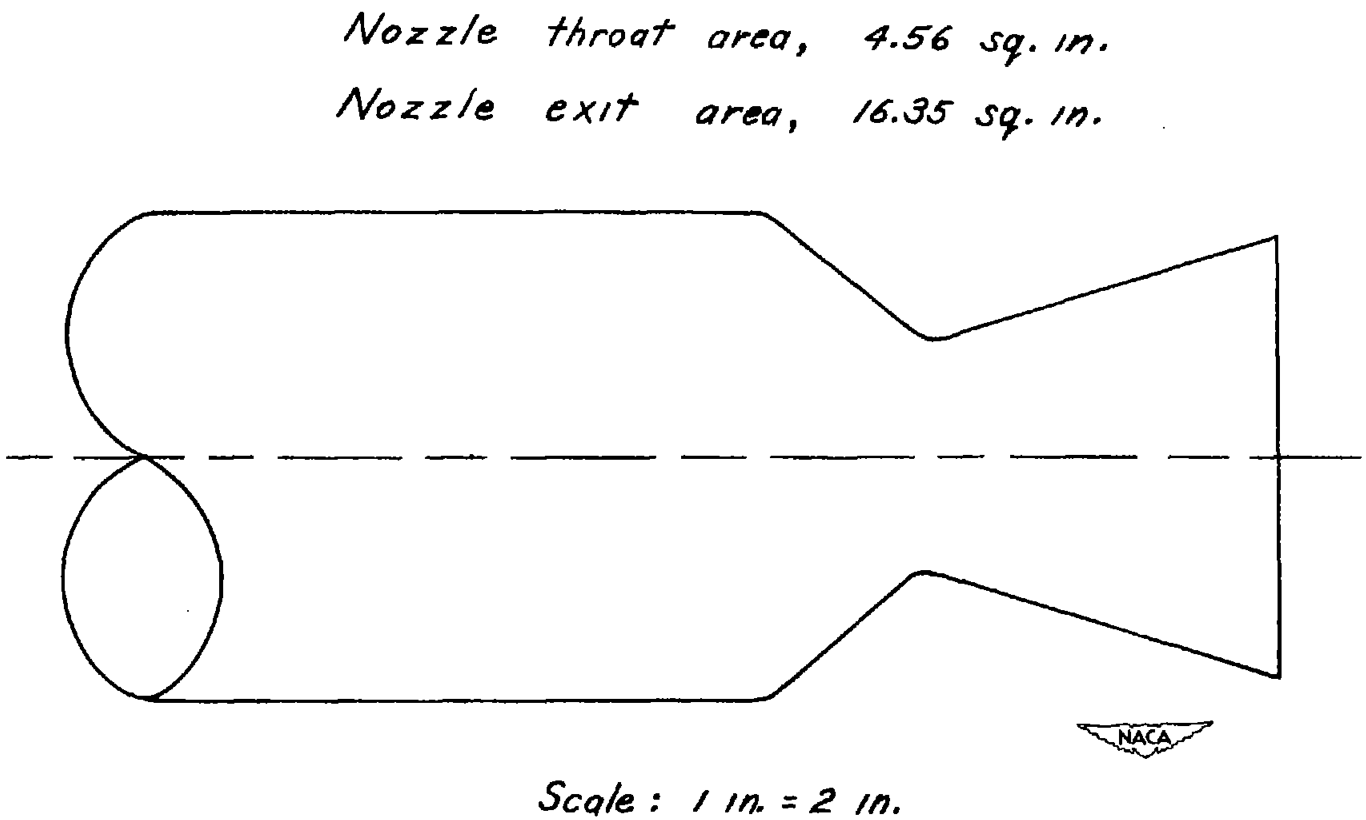


Figure 5.- Scale drawing of rocket nozzle, Bell X-1 number 2 airplane.

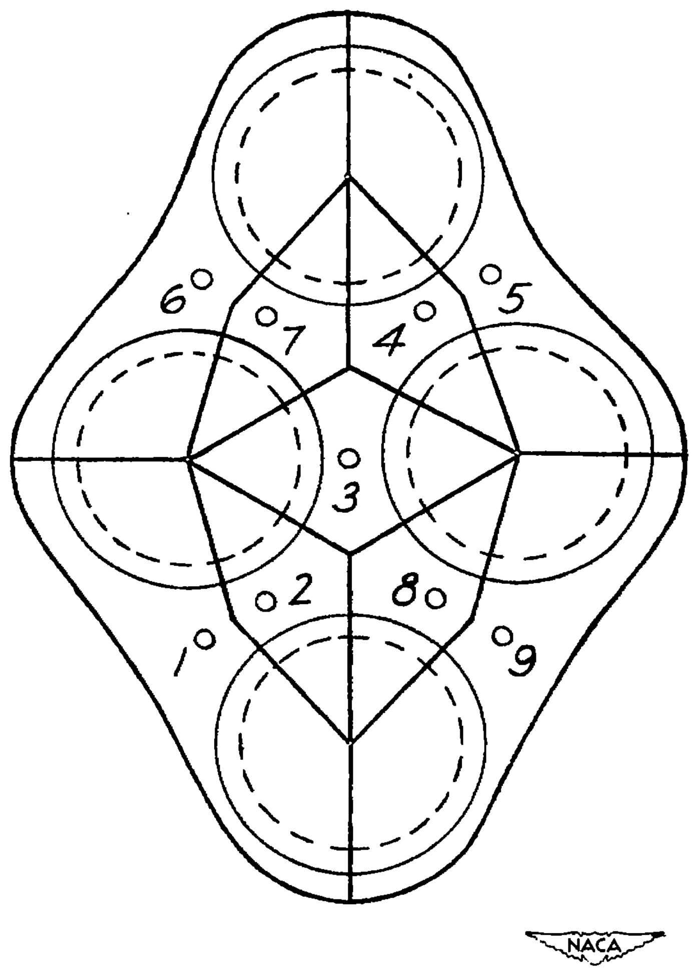


Figure 6.- Representative areas used with each respective orifice in the determination of base drag.

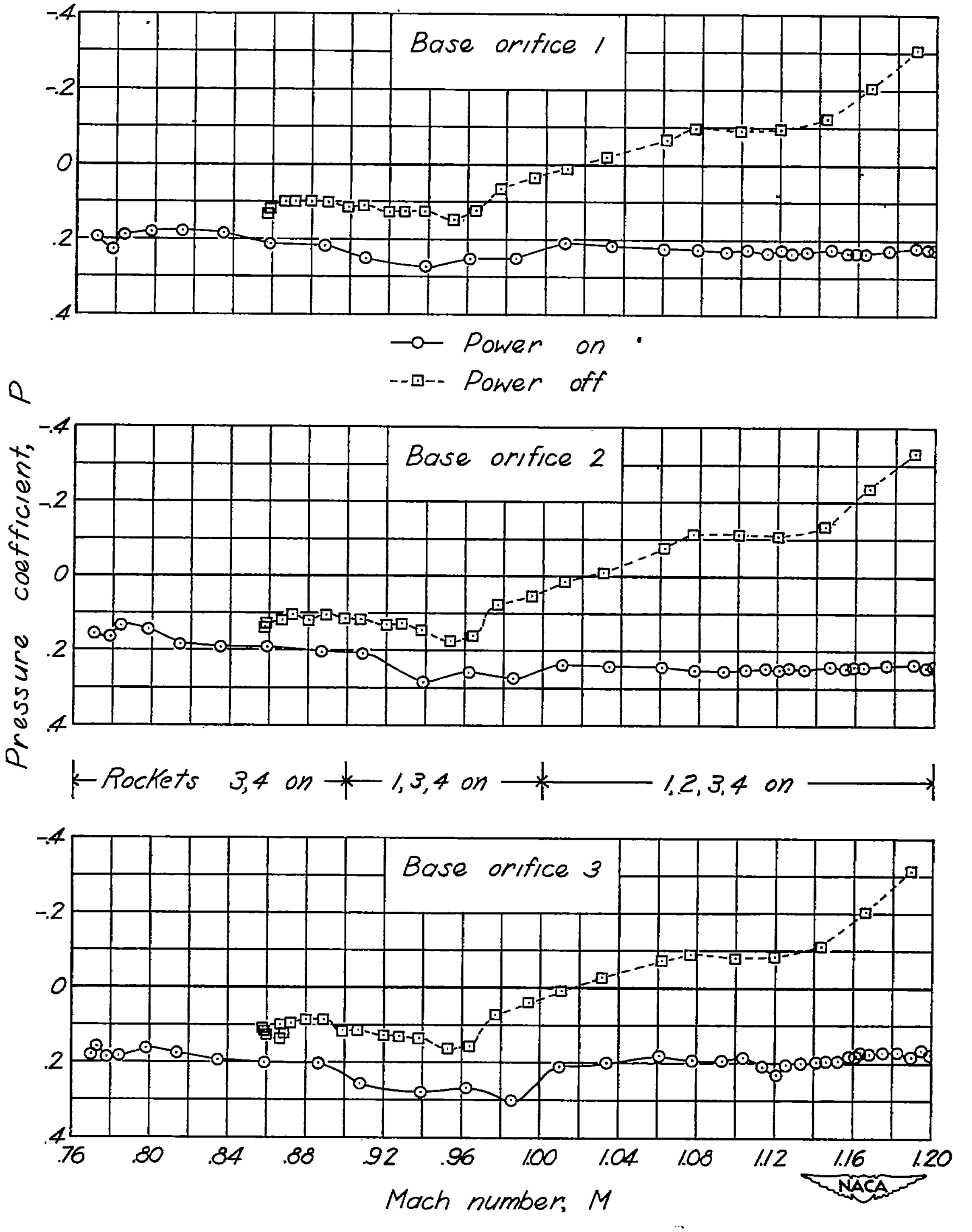
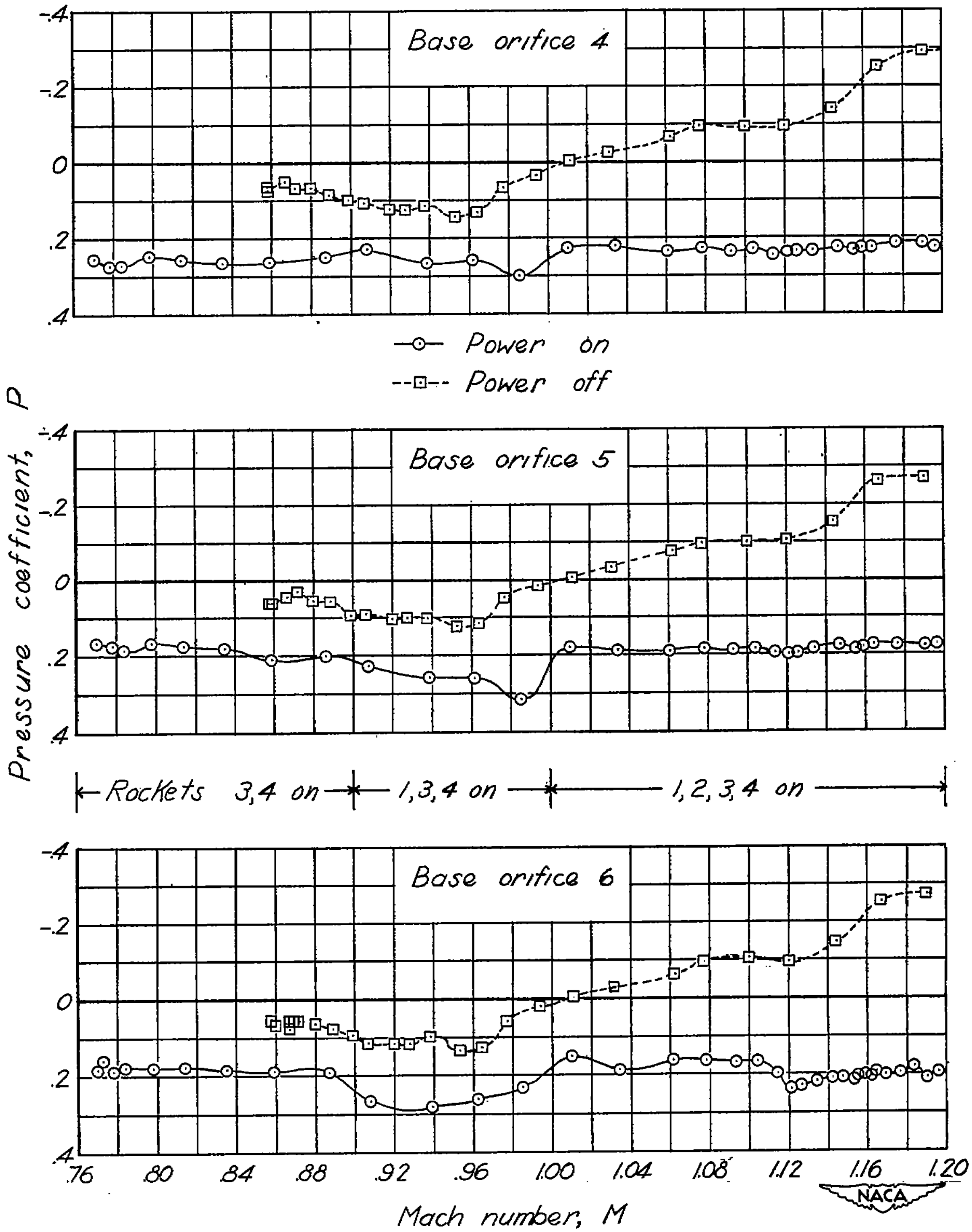


Figure 7.- Variation of pressure coefficient on fuselage base with Mach number in power-on and power-off flight on Bell X-1 airplane. $C_{N_A} \approx 0.4$.



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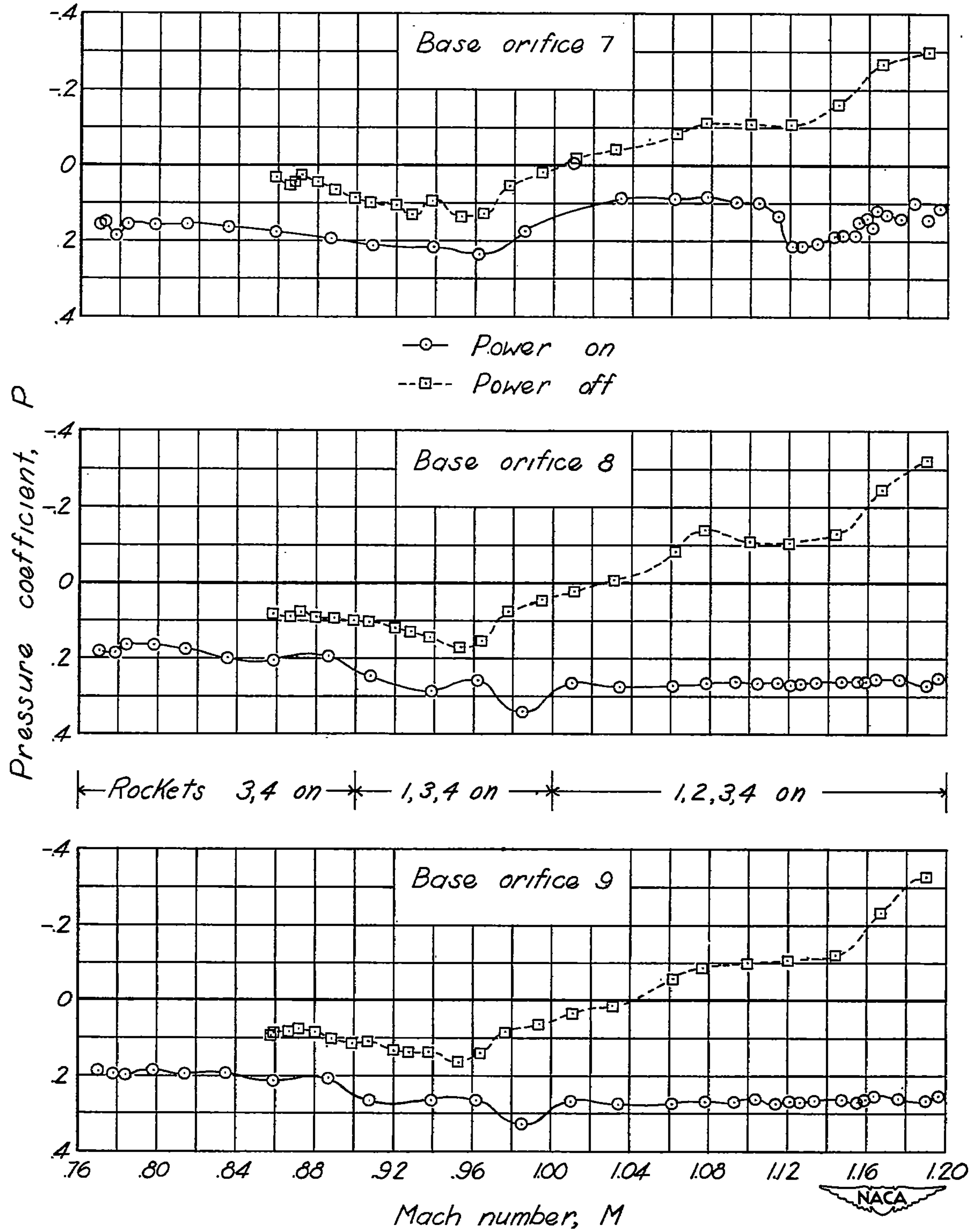

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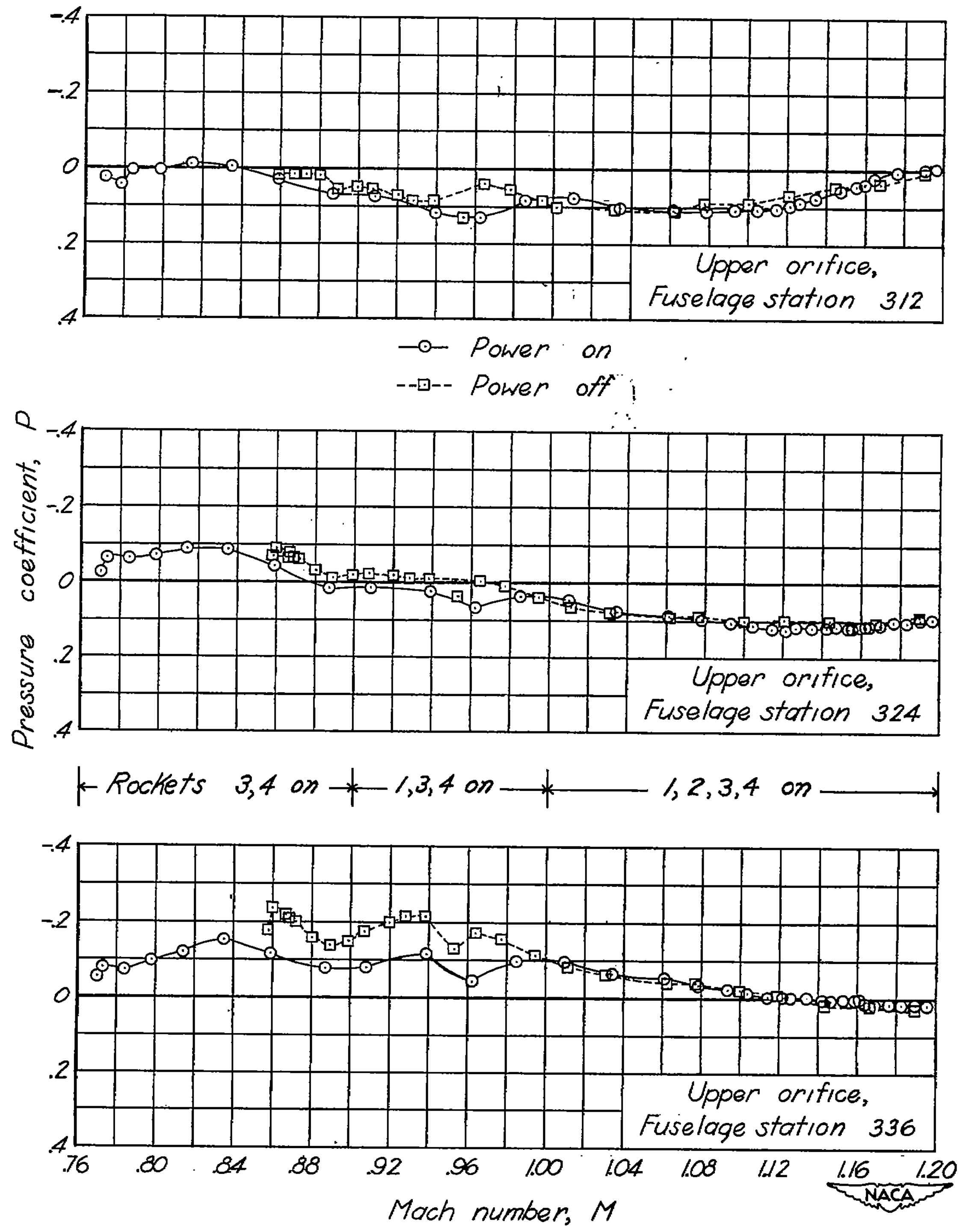

Figure 8.- Variation of pressure coefficient on fuselage side near base with Mach number in power-on and power-off flight of Bell X-1 airplane. Upper orifice row; $C_{N_A} \approx 0.4$.

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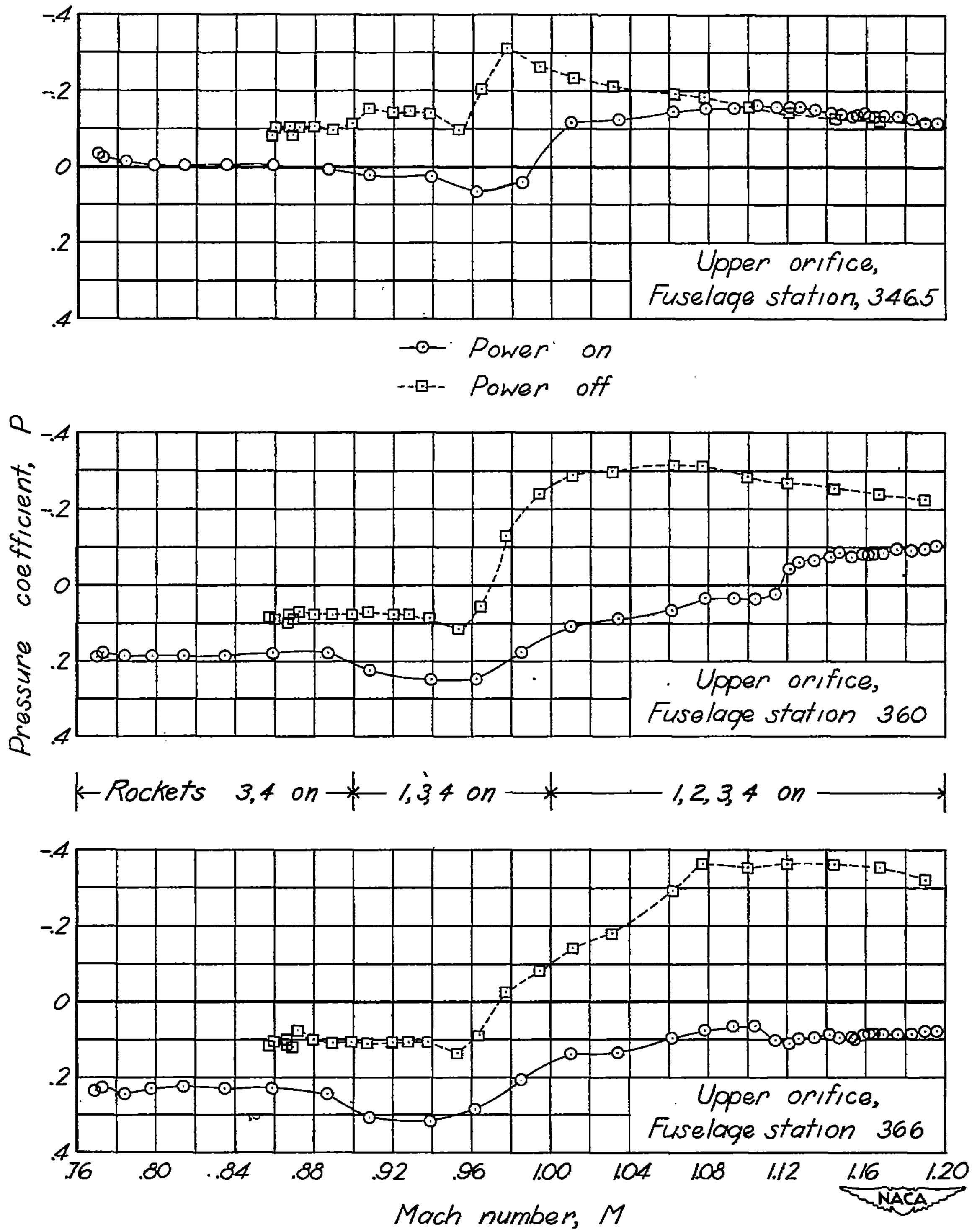

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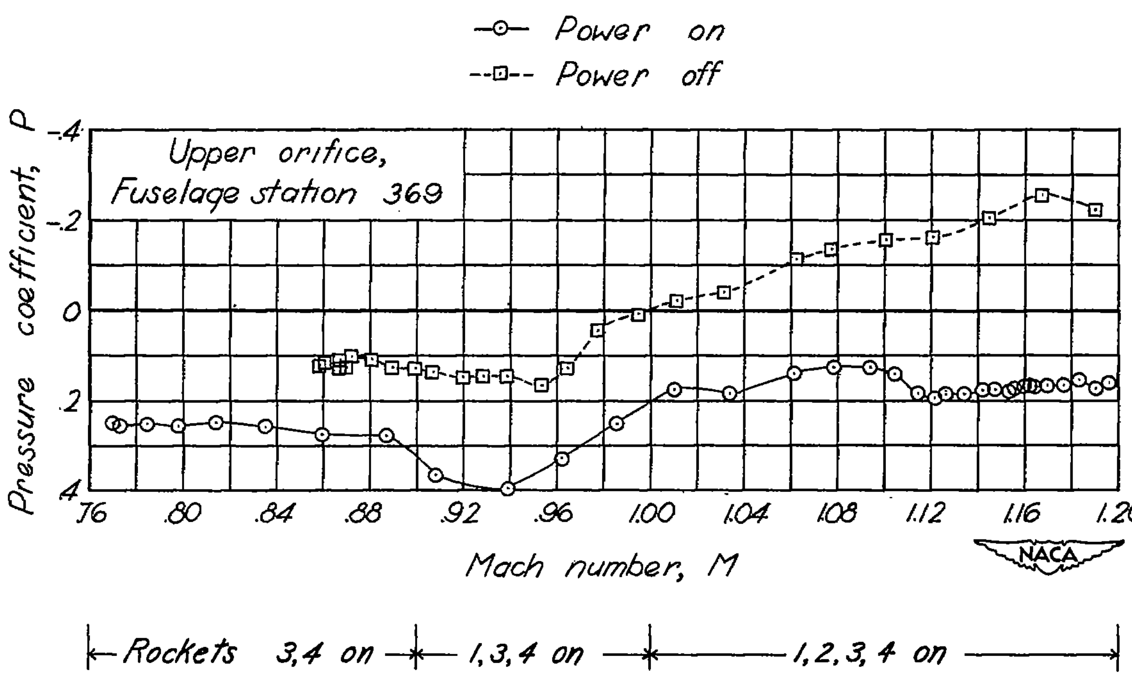

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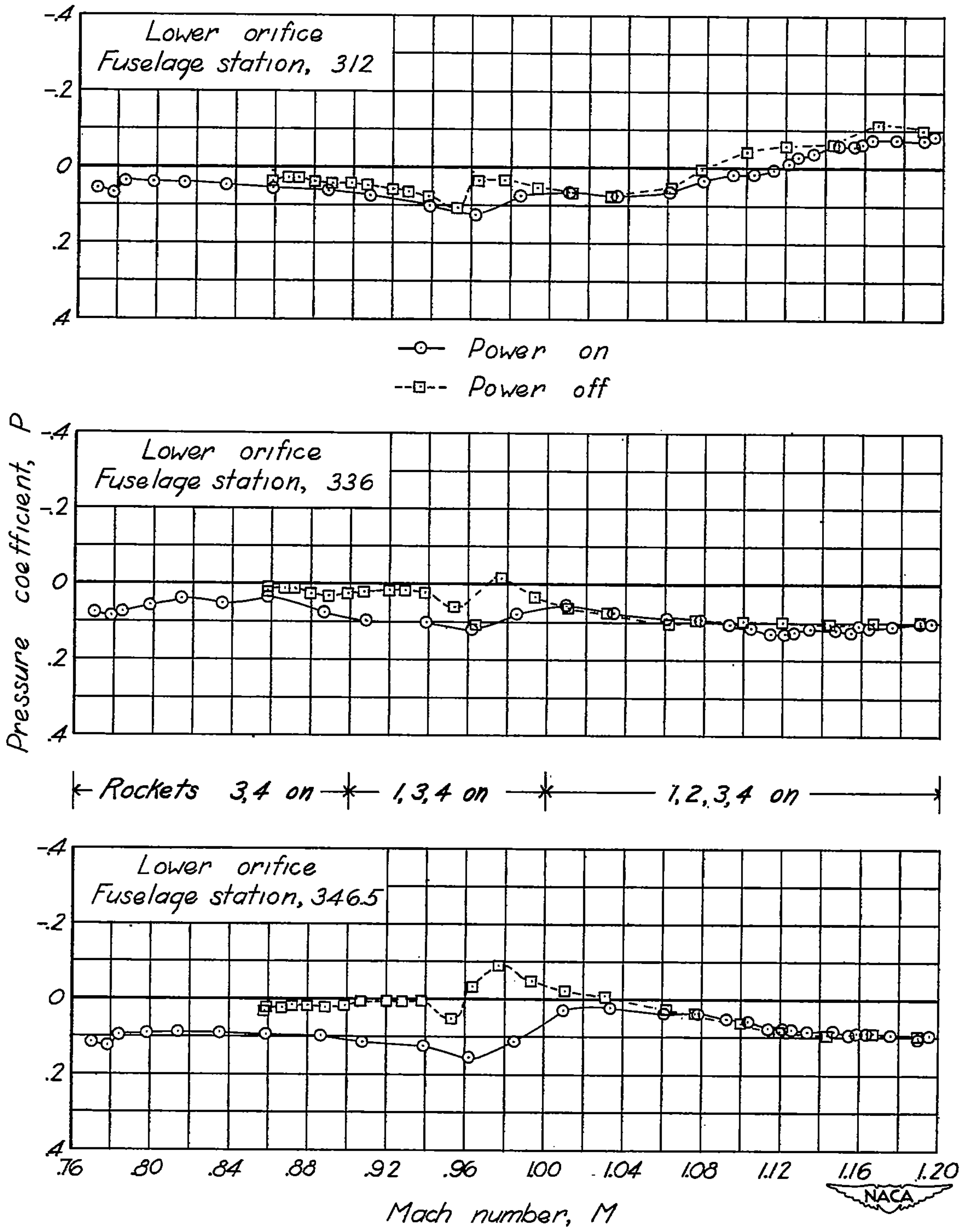


Figure 9.- Variation of pressure coefficient on fuselage side near base with Mach number in power-on and power-off flight of Bell X-1 airplane. Lower orifice row; $C_{N_A} \approx 0.4$.

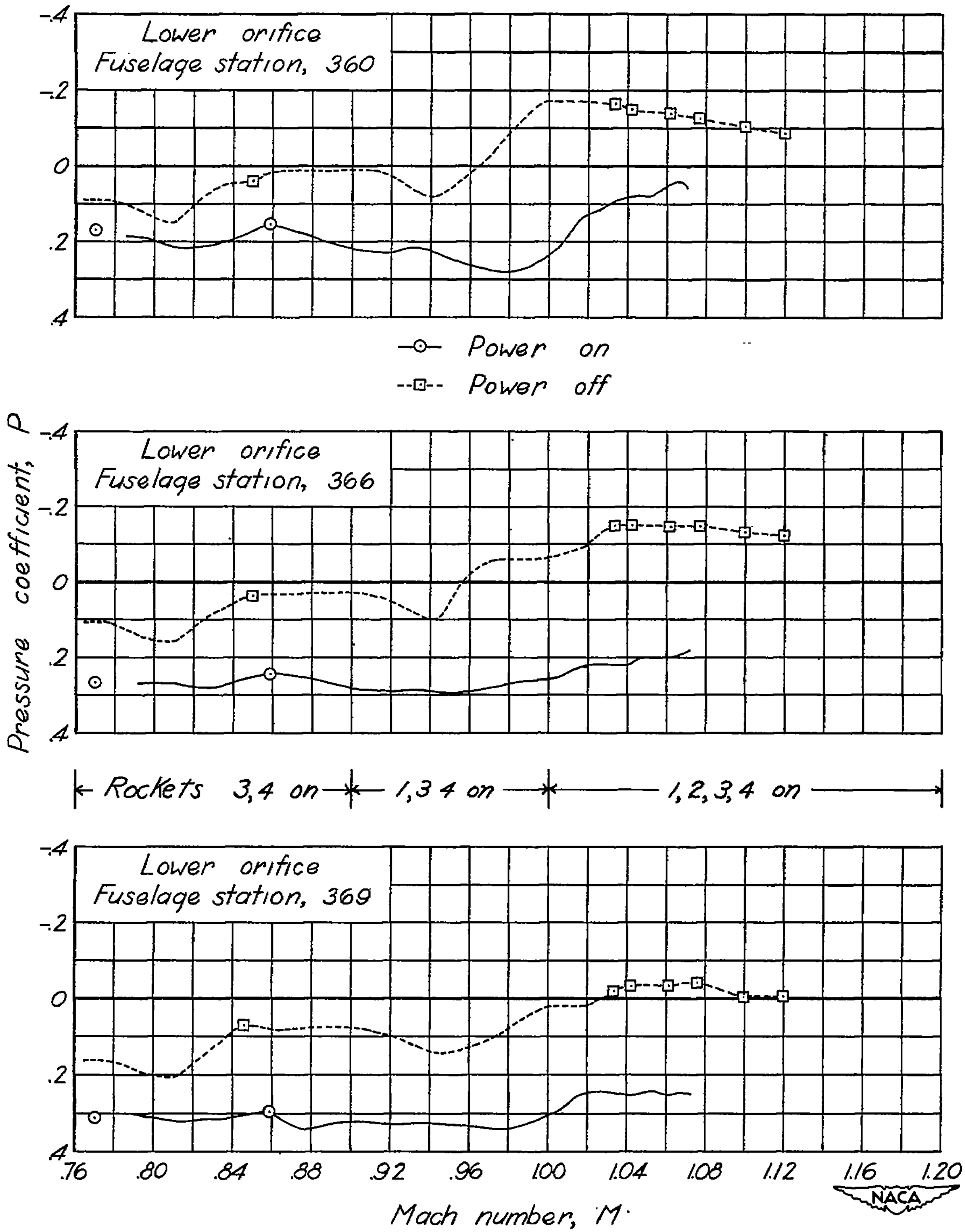


Figure 9.- Concluded.

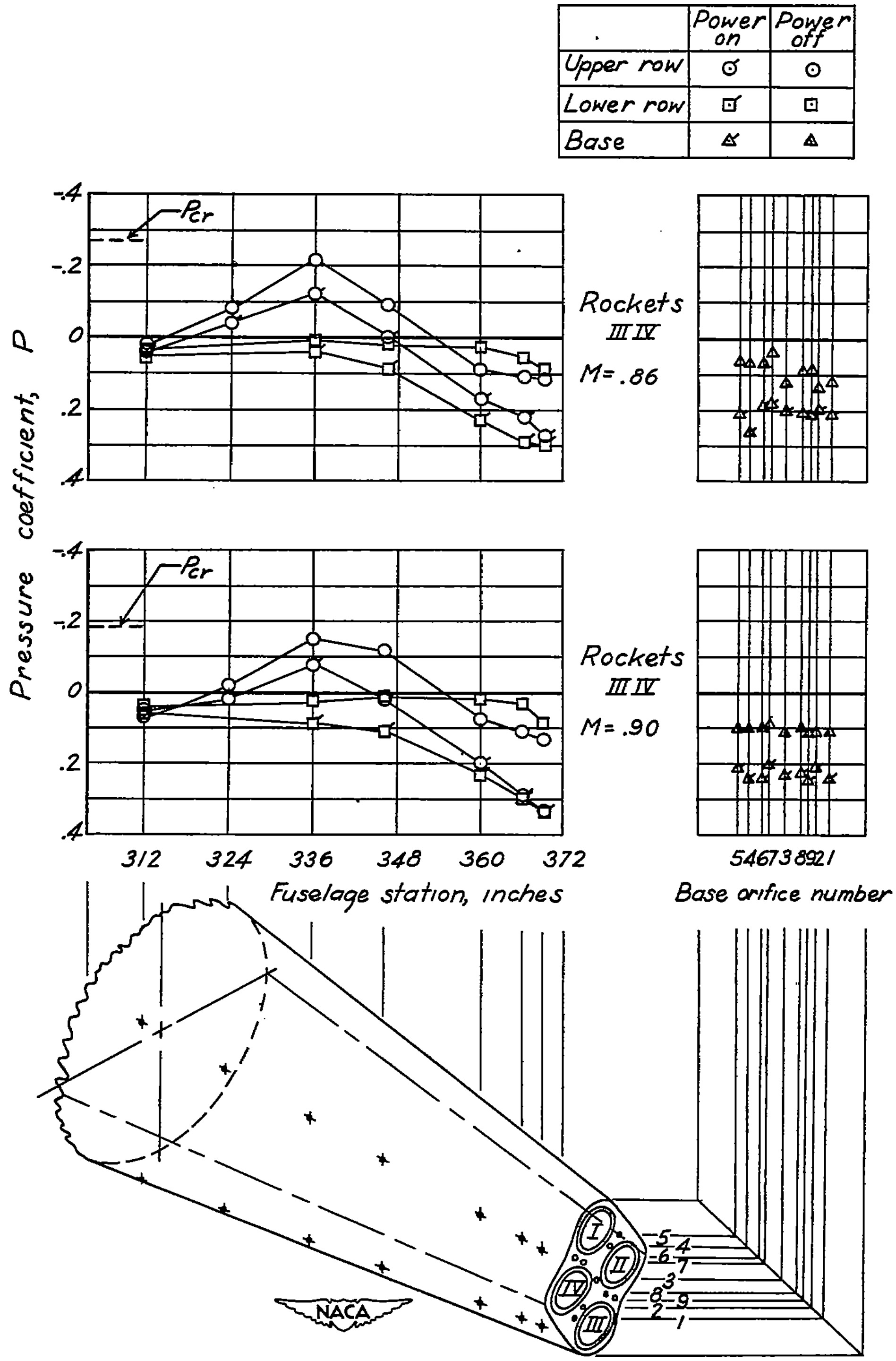
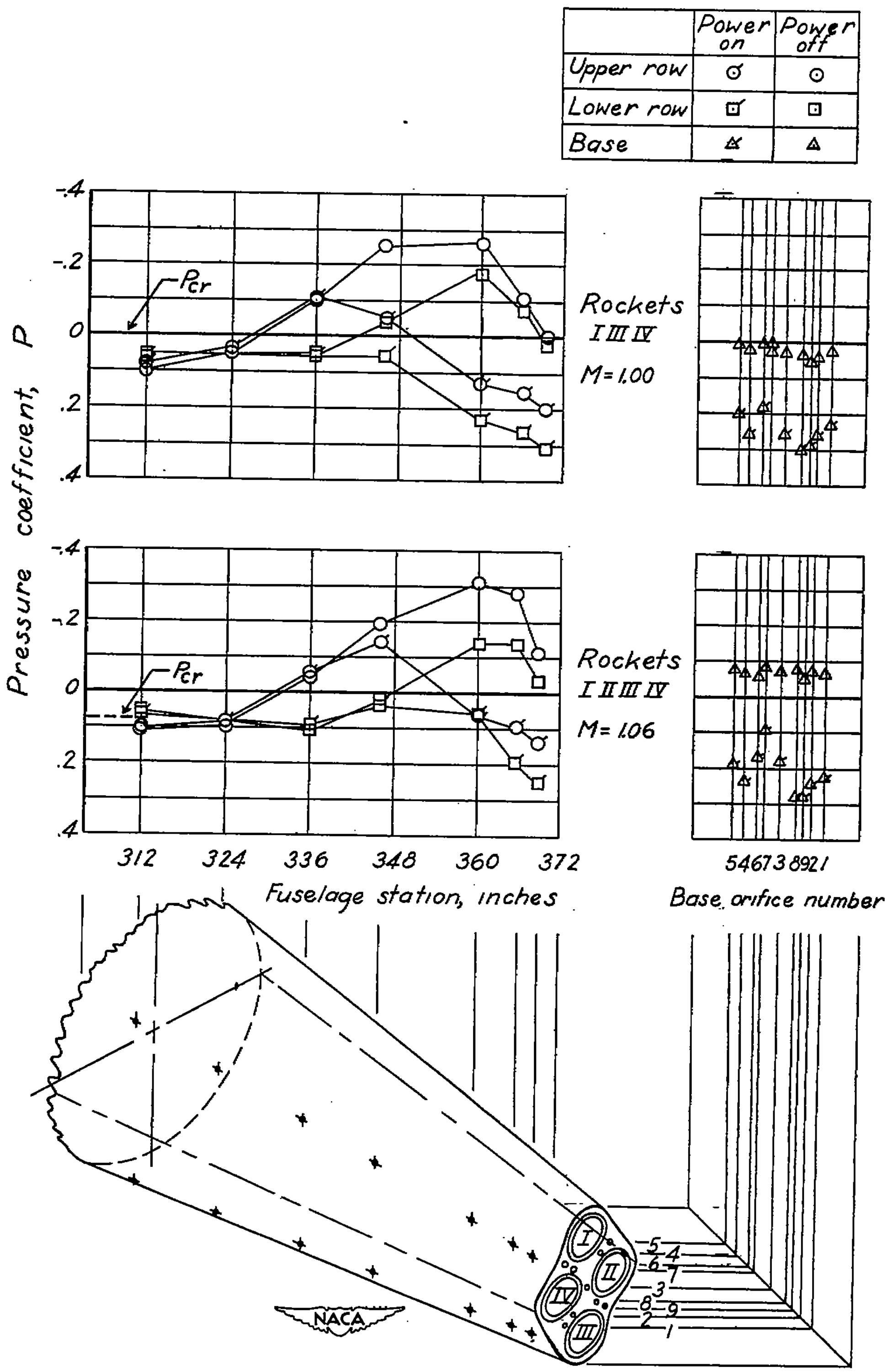


Figure 10.- Pressure distribution on and near fuselage base in power-on and power-off flight at various Mach numbers. $C_{N_A} \approx 0.4$.



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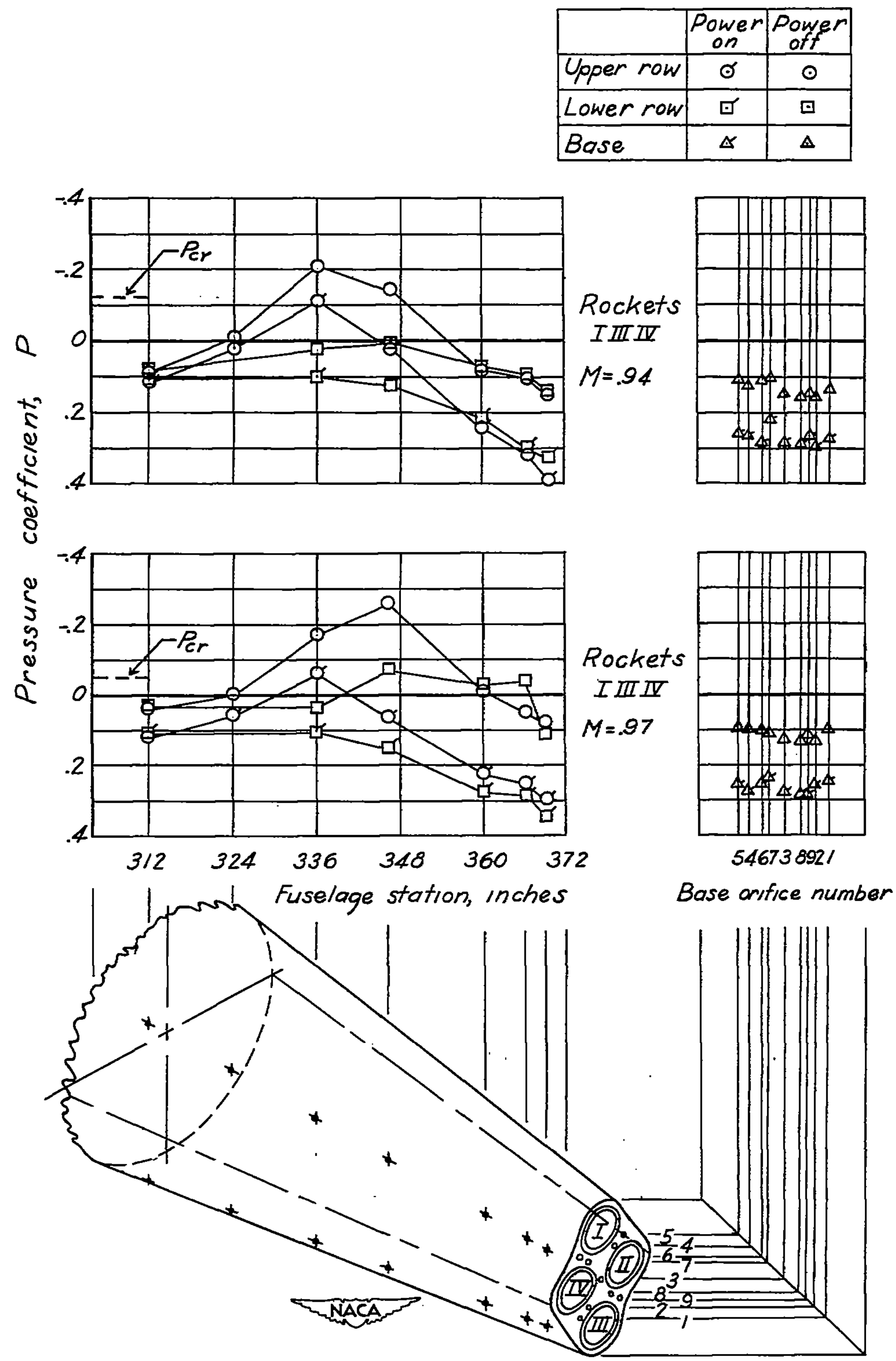

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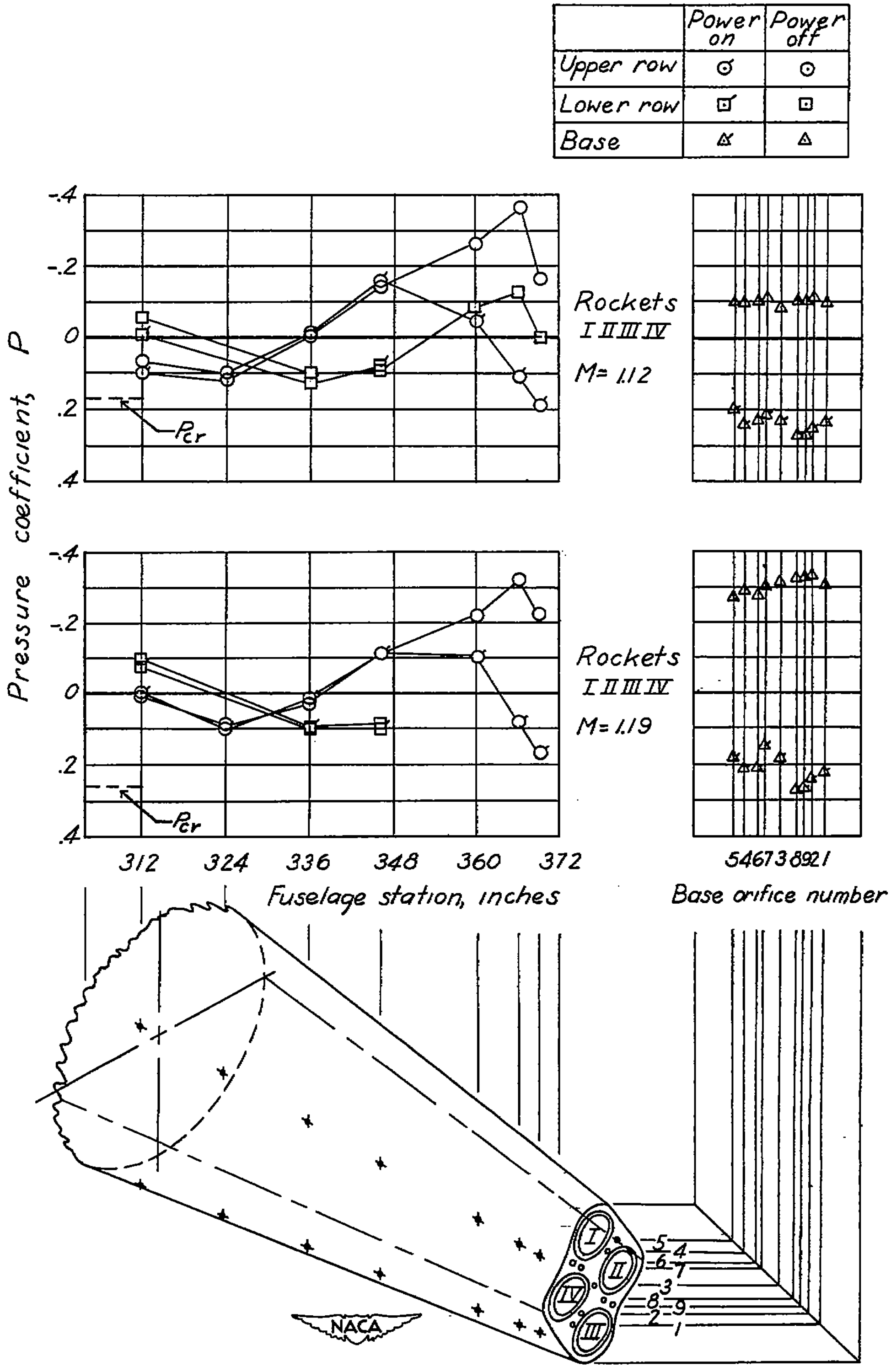

Figure 10.- Concluded.

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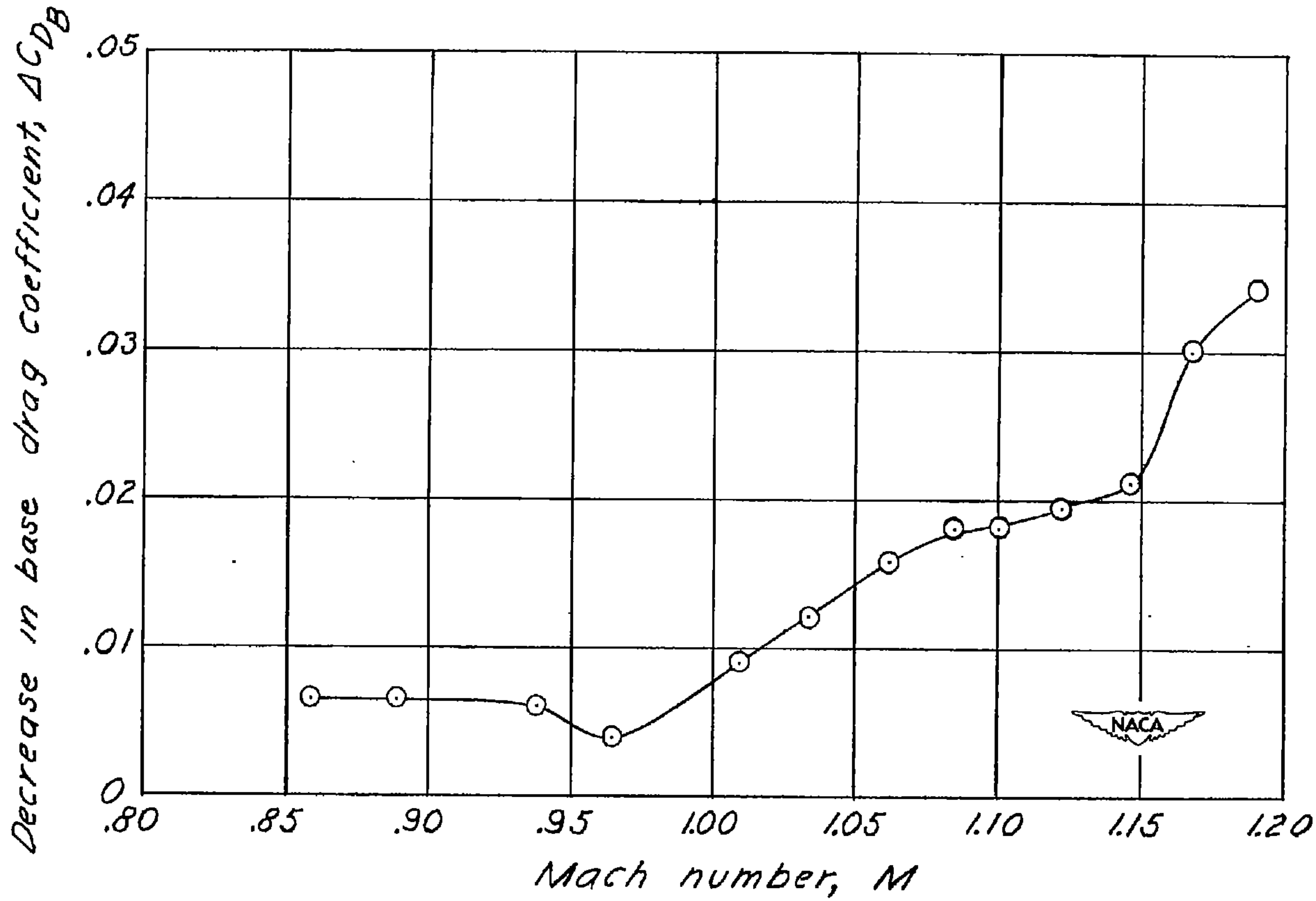

Figure 11.- Decrease with power of fuselage-base pressure-drag coefficient throughout the Mach number range of the tests. $C_{N_A} \approx 0.4$.

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